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ORIGINAL PAPER

Improving the assessment method of seed vigor in *Cunninghamia lanceolata* and *Pinus massoniana* based on oxygen sensing technology

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Abstract: Oxygen sensing technology was employed to study the rapid methods for seed vigor assessment of Chinese fir (*Cunninghamia lanceolata*) and Masson pine (*Pinus massoniana*). Firstly, seeds of five lots were performed using accelerated aging (AA) into three vigor levels. Then, four oxygen sensing indices, including increased metabolism time (IMT), oxygen metabolism rate (OMR), critical oxygen pressure (COP), relative germination time (RGT) and the control indices such as laboratory germination indices, dehydrogenase activity (DA), and electrical conductivity (EC) were analyzed by the tests of 15 samples. The results of correlation analysis between these indices and field emergence performances based on two-year and two-spot data showed that RGT and OMR should be indicated as the optimal oxygen sensing indices to rapidly and automatically evaluate seed vigor of Chinese fir and Masson pine, respectively. On the basis, one-variable linear regression equations were built to forecast their field emergence performances by the two oxygen sensing indices.

Keywords: *Cunninghamia lanceolata*; *Pinus massoniana*; seed vigor; oxygen sensing

Introduction

Chinese fir (*Cunninghamia lanceolata*) and Masson pine (*Pinus massoniana*) are widely distributed in China. They are important tree species for wood products industry and the pioneer tree species for afforestation. Lots of seeds are used for sowing each year. Seed quality is a crucial factor for successful afforestation. Over time, germination percentage is commonly used to evaluate seed quality of forest tree. However, there was difference between laboratory germination and field emergence. Even though seeds of different lots have the same germination percentage, their vigor levels are frequently different. Therefore, seed vigor index on behalf of their field emergence performances should be more suitable to evaluate seed quality. Nowadays, seed vigor test is mainly focused on physical, physiological, biochemical, histochemical methods (Yan et al. 2006). In our previous study, standard germination percentage (SGP), paper piercing germination percentage (PPGP), cold germination percentage (CGP), accelerated aging germination percentage (AAGP), soluble sugar (SS), volatile aldehyde (VA), dehydrogenase activity (DA), electrical conductivity (EC) were tested to improve seed vigor assessment of sweet corn (Zhao et al. 2007). Our results showed that these indices except for SGP were suitable to evaluate seed vigor of different genotypes. It was known that germination experiment is still the most effective method to evaluate seed quality and seed vigor of Chinese fir and Masson pine. However, their germination test needs a long experimental period (21 days). Considering laboratory germination test is time consuming, it is necessary to study the rapid methods for their seed vigor assessment.

In forest tree, some rapid methods such as accelerated aging (AA) test, enzyme activity test and electrical conductivity (EC) test were extensively studied (Singh and Bonner 2001). Tetrazolium staining is a method of International Seed Testing Association (ISTA) for seed viability test and is subsequently developed as a method for seed vigor test by means of dehydrogenase activity (DA) test. Since EC test is convenient and fast, it is extensively applied in seed vigor test of many tree species. Seed vigor of some tree species, such as *Pinus taeda* and *Pinus elliottii*, can be quickly assessed by DA test and EC test (Bonner 1986). According to lots of previous studies, however, DA and EC were lack of stability and accuracy.

Oxygen is necessary to seed germination. Thus, seed vigor should be able to be assessed by testing the oxygen consumption

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during germination. The oxygen sensing technology is developed based on the optical oxygen detection system by Netherlands ASTEC Global Seed Technology Corporation. The measurement of oxygen consumption by germinating seeds can bring deeper insight into the quality aspects of tested seed lots because oxygen consumption is directly related to energy production and indicative for different performance aspects in germination. Through the oxygen sensing technology, the measurement results are expressed in oxygen percentage over time graphs and a set of values are calculated by ASTEC software to analyze the quality of the tested samples.

The measurement of oxygen consumption is fast because it ends up with radicle protrusion in general. Furthermore, this test is automatically conducted by oxygen sensing machinery called Q2 instrument and is well suitable for large-scale testing. The oxygen sensing technology is revolutionary for seed testing in basic research and commercial operations alike. However, the oxygen sensing technology is only successfully applied to evaluate seed vigor of a few crops such as sugar beet (Zhao et al. 2009). Whether it is suitable for seed vigor assessment of Chinese fir and Masson pine need be further studied. Besides, some traditional methods such as laboratory germination test, electrical conductivity test and dehydrogenase activity test were also conducted as control methods in this study. Correlation analysis was performed between these test indices and field emergence performances based on two-year and two-spot data. The focus of this study was to develop the rapid assessment methods for seed vigor of Chinese fir and Masson pine. Our study was of great guidance significance to seedling raising and afforestation in Chinese fir and Masson pine.

Materials and methods

Plant materials

Five lots of Chinese fir and Masson pine seeds with the second generation were bought from Zhejiang Forestry Seed and Seedling Administration Station in 2009 and 2010. Seeds of each lot were averagely sampled into three shares. Two shares of them were performed using accelerated aging at 40°C and 100% relative humidity for 30 h and 48 h in a LH-150S aging cabinet (Tuopu, China). Thus, 15 samples were gained and were stored at 4°C before use.

Laboratory germination

The laboratory germination test was conducted on three replicates of 100 seeds per sample on the top of two layers of filter paper. Seeds were incubated for 21 days at 25°C with alternating 16 h dark and 8 h light. The number of seedlings was recorded every day after germination until no further germination. Germination percentage (GP) was calculated at the 21st day. Germination index (GI) was calculated by the following formula.

$$GI = \sum Gt / Dt$$

Gt: The number of germinated seeds at *t*th day; Dt: The days of germinated seeds

Field emergence test

Two spots were chosen in Hangzhou and Wenzhou, Zhejiang, China. Hangzhou belongs to subtropical monsoon area and Wenzhou belongs to middle subtropical monsoon area. In 2009, the field emergence (FE) test was conducted at the Botanical Garden of Zhejiang Agriculture & Forestry University (ZAFU) and an experimental site of Whenzhou from May 1st to May 31st. In the 10 cm soil layer, the average temperature was 15.2°C, 20.5°C and the average relative water content was 70.6% and 68.8% in Hangzhou and Whenzhou, respectively. In 2010, the FE test was conducted at the farm of ZAFU and Whenzhou Academy of Agricultural Science from May 15th to June 15th. In the 10 cm soil layer, the average temperature was 16.8°C, 21.7°C and the average relative water content was 67.9% and 70.1% in Hangzhou and Whenzhou, respectively. In both years, the FE test was conducted using a complete random design on three replicates of 100 seeds per sample. The plant and row spacing was 20 cm × 30 cm. Seeds were sown in soil covered with 1−2 cm deep plant ash. The number of seedlings was recorded every day after emergence until no further emergence. Field emergence percentage (FEP) and field emergence speed (FEI) was calculated on the average of two-spot data. FEI, which represents field emergence speed, was calculated referring to the above formula of GI.

Dehydrogenase activity test

The DA test referred to the method of Zhao et al. (2007). Ten seeds were randomly chosen and then performed on length cutting along the center of seed embryo. A half of them were placed into a test tube with 5 ml 0.2% triphenyl tetrazolium chloride (TTC) and the tube was covered to keep staining at 25°C for 24 h. Next, half-embryo seeds were taken out, put into another tube and 5 ml anhydrous ethanol was added, then placed at 25°C for another 24 h. Finally, the extraction solution was used to determine the OD value at 490 nm. The test was conducted on three replicates.

Electrical conductivity test

The EC test referred to the method of ISTA (2005). The test was conducted on three replicates of 100 seeds per sample. Seeds were soaked in 50 ml distilled water at 25°C for 24 h. EC was then tested by a DDS-307A conductivity meter (Shanghai, China). The conductivity per g of seed weight of each replicate for each sample was calculated according to the following formula: EC ($\mu S.cm^{-1}.g^{-1}$) = (conductivity reading – background reading)/seed weight.

Oxygen sensing test

The oxygen sensing test was conducted on four replicates of 48 seeds per sample quantified energy use by measuring oxygen consumption of individual seed, planted in 12 microtiter plates of 48 wells (one seed per well) with 1000 μl 0.5% agar in 2.0 ml tube. The test was performed at an interval of 60 min until 240 h at 25°C. The information was inputted into Q2 operation software. The seeds were airproofed with photosensitive material and oxygen content (the relative value, %) was measured by Q2 instrument (ASTEC Global, Netherlands). Thus, oxygen content of each hour was automatically recorded.

Data analysis

ANOVA analysis, correlation analysis and regression analysis were carried out with SAS v6.12. Four ASTEC values including increased metabolism time (IMT), oxygen metabolism rate (OMR), critical oxygen pressure (COP), relative germination time (RGT) were calculated by Q2 analytical software (ASTEC Global, Netherlands).

Results

Seed quality assessment

Seed quality evaluated by the different tests was given in Table 1. Germination tests in both years including laboratory and field ones well ranked the seed lots into various quality groups on the basis of LSD means separation generally following the same pattern: No aging > aging for 30 h > aging for 48 h. Mean field values were generally lower than laboratory ones in both years. Furthermore, seeds of Masson pine generally had higher germination values than those of Chinese fir in both years.

For Chinese fir, DA and RGT in both years were able to rank the seed lots into various quality groups on the basis of LSD means separation generally following the same pattern: No aging < aging for 30 h < aging for 48 h. However, EC, IMT, OMR, COP were not able to rank the seed quality with different vigor levels by aging treatment in both years.

Table 1. Seed quality evaluated by different test

Test year	Tree species	Aging treatment	Germination percentage (GP, %)	Germination index (GI)	Field emergence percentage (FEP, %)	Field emergence speed (FEI)	Dehydrogenase activity (DA, OD_{490})	Electrical conductivity (EC, $\mu S\cdot cm^{-1}\cdot g^{-1}$)	Increased metabolism time (IMT, h)	oxygen metabolism rate (OMR, $\%\cdot h^{-1}$)	Critical oxygen pressure (COP, %)	Relative germination time (RGT, h)
2009	Chinese fir	No aging	62.7 a	5.9 a	42.9 a	2.0 a	0.8 c	269.8 a	58.0 b	0.7 a	29.1 b	218.0 c
		Aging for 30 h	59.1 b	5.1 b	36.3 b	1.2 b	1.0 b	222.0 b	61.5 ab	0.6 b	30.9 b	279.7 b
		Aging for 48 h	55.5 c	4.4 c	26.5 c	0.9 c	1.3 a	208.2 b	62.8 a	0.6 b	35.1 a	326.9 a
	Masson pine	No aging	79.2 a	14.7 a	57.6 a	3.4 a	1.5 a	138.0 c	25.1 b	0.7 a	31.2 b	130.9 b
		Aging for 30 h	65.9 b	10.4 b	43.7 b	2.5 b	1.5 a	242.8 b	36.5 a	0.6 b	35.1 a	132.1 b
		Aging for 48 h	52.9 c	7.7 c	35.5 c	1.3 c	1.3 b	353.9 a	38.1 a	0.5 c	36.7 a	148.3 a
2010	Chinese fir	No aging	55.4 a	6.0 a	37.3 a	3.5 a	0.6 c	284.2 a	51.3 b	0.6 a	31.3 bc	165.0 c
		Aging for 30 h	51.7 b	5.1 b	24.1 b	2.2 b	0.9 b	276.0 ab	51.7 b	0.6 a	37.9 b	175.5 b
		Aging for 48 h	47.3 c	4.4 c	18.0 c	1.7 c	1.2 a	270.5 b	56.7 a	0.5 b	47.6 a	186.4 a
	Masson pine	No aging	87.4 a	14.6 a	59.4 a	4.7 a	1.9 a	163.5 c	36.3 b	0.9 a	36.6 b	184.1 b
		Aging for 30 h	74.1 b	12.0 b	43.7 b	3.2 b	1.8 b	226.1 b	38.9 b	0.7 b	37.4 b	202.1 a
		Aging for 48 h	68.9 c	8.8 c	36.1 c	2.1 c	1.8 b	362.9 a	48.3 a	0.5 c	40.0 a	204.6 a

Means above a row by the same letter are not significantly different (p>0.05).

For Masson pine, EC and OMR in both years were able to rank the seed lots into various quality groups on the basis of LSD means separation generally following the pattern: No aging < aging for 30 h < aging for 48 h and No aging > aging for 30 h > aging for 48 h, respectively. IMT ranked the seed quality with different vigor levels by aging treatment on the contrary order in 2009 and 2010. However, DA, COP, RGT were not able to rank the seed quality with different vigor levels by aging treatment in both years.

Correlations between traditional test methods and field emergence performances

For Chinese fir, positive correlations existed between GP, GI, EC and FEP, FEI and negative correlations existed between DA and FEP, FEI in both years (Table 2). However, there were no significant correlations between all traditional test indices and field emergence performances including FEP and FEI except GI in 2010. However, significant correlations existed between all traditional test indices and FEP, FEI when two-year data were analyzed together.

For Masson pine, there were significant positive correlations between laboratory germination test indices and field emergence performances in both years (Table 3). There were also significant negative correlations between EC and FEP, FEI. However, no significant positive correlations existed between DA and field emergence performances. When two-year data were analyzed together, the results similar as that of Chinese fir were obtained.

The results suggested that GP, GI, EC were suitable to evaluate seed vigor of Masson pine except DA.

Table 2. Correlation coefficients between traditional test indices and field emergence performances in Chinese fir

Traditional test indices	2009 (n=15)		2010 (n=15)		Total (n=30)	
	FEP/%	FEI	FEP/%	FEI	FEP/%	FEI
GP/%	0.377	0.374	0.282	0.279	0.541**	0.604***
GI	0.450	0.446	0.539*	0.520*	0.443*	0.395*
DA/OD_{490}	-0.110	-0.158	-0.305	-0.305	-0.487**	-0.590***
$EC/\mu S \cdot cm^{-1} \cdot g^{-1}$	0.068	0.072	0.473	0.511	0.499**	0.575***

*significant correlation at p<0.05, **significant correlation at p<0.01, ***significant correlation at p<0.001.

Table 3. Correlation coefficients between traditional test indices and field emergence performances in Masson pine

Traditional test indices	2009 (n=15)		2010 (n=15)		Total (n=30)	
	FEP/%	FEI	FEP/%	FEI	FEP/%	FEI
GP/%	0.816***	0.761***	0.642**	0.569*	0.669***	0.756***
GI	0.796***	0.739**	0.693**	0.642**	0.678***	0.671***
DA/OD_{490}	0.326	0.325	0.233	0.325	0.199	0.251
$EC/\mu S \cdot cm^{-1} \cdot g^{-1}$	-0.832***	-0.777***	-0.583*	-0.606*	-0.678***	-0.662***

*significant correlation at p<0.05, **significant correlation at p<0.01, ***significant correlation at p<0.001.

Correlations between oxygen sensing indices and field emergence performances

Oxygen sensing indices include IMT, OMR, COP, RGT. In our results, these oxygen sensing indices were significantly correlated with their laboratory germination performances (Table 4). Considering the field emergence performances were the most direct indices for seed vigor assessment, the correlation analysis between oxygen sensing indices and FET, FEI was performed.

Table 4. Correlation coefficients between oxygen sensing indices and laboratory germination performances

Oxygen sensing indices	Chinese fir (n=30)		Masson pine (n=30)	
	GP/%	GI	GP/%	GI
IMT/h	-0.539**	-0.599***	-0.557**	-0.556**
$OMR/\% \cdot h^{-1}$	0.390*	0.577***	0.535**	0.707***
COP/%	-0.557**	-0.425*	-0.552**	-0.711***
RGT/h	-0.869***	-0.468**	-0.564**	-0.369*

*significant correlation at p<0.05, **significant correlation at p<0.01, ***significant correlation at p<0.001.

For Chinese fir, it can be seen from Table 5 that there were positive correlations between IMT, OMR and FEP, FEI; negative correlations between COP, RGT and FEP, FEI. IMT was significantly correlated with FEP, FEI in 2010 only. OMR was not significantly correlated with FEP, FEI in either year. COP was significantly correlated with FEP, FEI in 2010 only. RGT was significantly correlated with FEP, FEI in either year. When two-year data were analyzed together, there were not significant correlations between IMT, OMR and FEP, FEI while there were significant correlations between COP, RGT and FEP, FEI. These results suggested that RGT was the optimal index to evaluate seed vigor of Chinese fir.

Table 5. Correlation coefficients between oxygen sensing indices and field emergence performances in Chinese fir

Oxygen sensing indices	2009 (n=15)		2010 (n=15)		Total (n=30)	
	FEP/%	FEI	FEP/%	FEI	FEP/%	FEI
IMT/h	0.139	0.169	0.520*	0.524*	0.225	0.136
$OMR/\% \cdot h^{-1}$	0.266	0.234	0.383	0.433	0.161	0.142
COP/%	-0.372	-0.344	-0.517*	-0.521*	-0.403*	-0.369*
RGT/h	-0.696**	-0.680**	-0.692**	-0.695**	-0.644***	-0.700***

*significant correlation at p<0.05, **significant correlation at p<0.01, ***significant correlation at p<0.001.

For Masson pine, it can be seen from Table 6 that there were also positive correlations between IMT, OMR and FEP, FEI; negative correlations between COP, RGT and FEP, FEI. IMT was significantly correlated with FEP, FEI in 2010 only. OMR was significantly correlated with FEP, FEI in either year. COP was not significantly correlated with FEP, FEI in either year. RGT was significantly correlated with FEP, FEI in 2010 only. When two-year data were analyzed together, there were significant correlations between OMR only and FEP, FEI. These results suggested that OMR was the optimal index to evaluate seed vigor of Masson pine.

Table 6. Correlation coefficients between oxygen sensing indices and field emergence performances in Masson pine

Oxygen sensing indices	2009 (n=15)		2010 (n=15)		Total (n=30)	
	FEP/%	FEI	FEP/%	FEI	FEP/%	FEI
IMT/h	0.197	0.179	0.599*	0.614*	0.330	0.251
$OMR/\% \cdot h^{-1}$	0.552*	0.613*	0.613*	0.566*	0.542**	0.622***
COP/%	-0.116	-0.211	-0.281	-0.194	-0.181	-0.179
RGT/h	-0.212	-0.225	-0.516*	-0.591*	-0.241	-0.229

*significant correlation at p<0.05, **significant correlation at p<0.01, ***significant correlation at p<0.001.

Prediction for field emergence performances by oxygen sensing indices

According to the above correlation analysis, there were differences in the prediction model for field emergence performances between Chinese fir and Masson pine based on oxygen sensing technology. RGT and OMR were the optimal indices for seed vigor assessment of Chinese fir and Masson pine, respectively. On the basis of two-year and two-spot average data, FEP and FEI of Chinese fir were predicted by RGT as the regression equations of y = -0.1362x + 63.219 and y = -0.0107x + 4.3188, respectively (Fig. 1A and Fig. 1B). FEP and FEI of Masson were predicted by

OMR as the regression equations of $y = 70.54x + 3.4126$ and $y = 4.8301x - 0.3692$, respectively (Fig. 2A and Fig. 2B).

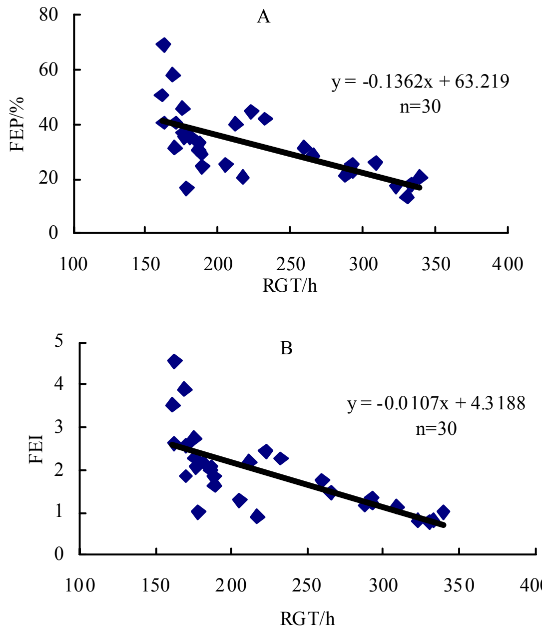

Fig. 1 Regression relationship between RGT and field emergence performances of Chinese fir

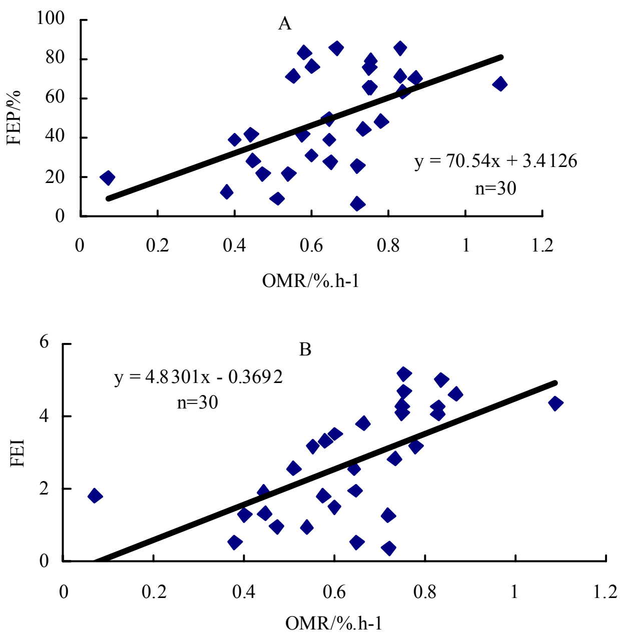

Fig. 2 Regression relationship between OMR and field emergence performances of Masson pine

Discussion

The concept of seed vigor was first recognized in 1876 by Nobbe and there have been many reviews of the subsequent development of the concept (Powell 2006). Perry (1978) considered that seed vigor was a sum of those properties that determined the activity and level of performance of seed lots of acceptable germination in a wide range of environments. Based on the consideration, it was defined by ISTA as “Seed vigour comprises those seed properties which determine the potential for rapid uniform emergence, and development of normal seedlings under a wide range of field conditions” (McDonald 1980). Thus, seed vigor is not a single measurable property, but is an important quality parameter which needs to be evaluated to supplement germination and viability tests to gain insight into the performance of a seed lot in the field. The definition of seed vigor emphasizes the relationship between testing indices and field emergence performances. Our studies have demonstrated this association existed between oxygen sensing indices and FEP, FEI for Chinese fir and Masson pine and these values have ability to rank seed qualities and predict field emergence performances.

Seed vigor is usually very low even though laboratory germination percentage was very high (Wilson et al. 1998). Seedling emergence rates in the field experiment were much lower than those in the greenhouse experiment conducted in *Schima mertensiana*, a tree native to the Ogasawara (Bonin) Islands, in the northwestern Pacific Ocean (Hata et al. 2010). Our research showed that GP did not significantly correlate with field emergence performances of Chinese fir in both years. The result was also similar to our previous study in sweet corn (Zhao et al. 2007). GI represents germination speed, which is one of vigor indices. GI can better reflect vigor status than GP. In our research, GI was significantly correlated with field emergence performances in 2010 while it failed to significantly correlate with those in 2009. In Masson pine, both GP and GI were significantly correlated with field emergence performances in both years. Furthermore, GP and GI were significantly correlated with field emergence performances when two-year data were analysed together in each species. Our study showed that this association existed between laboratory germination and field emergence in bigger samples (n=30) in Chinese fir than in Masson pine. The results suggested that seed vigor evaluated by laboratory germination was species-dependent.

Dehydrogenase is the enzyme that has been practically applied in vigor assessment (Moore 1973). DA has been reported as a reliable index in seed vigor assessment of some agricultural crops such as corn (Zhao et al. 2007). In our study, however, DA is not suitable to evaluate seed vigor of both Chinese fir and Masson pine. The result was contrary to that of Fu et al. (1988). Furthermore, negative correlation existed between DA and seed vigor of Chinese fir in our study. DA is known to decline as seed aging under natural conditions. In our results, DA ascended as aging time goes in Chinese fir while declined in Masson pine. The cause is likely related to the nature of artificial aging and natural aging. According to a number of studies, there was difference in the mechanisms of two kinds of aging (Stewart and Bewley 1980; Yan et al. 2006). Natural aging results in a slow change of seed vigor while artificial aging results in a fast change. After artificial accelerated aging, compared with high vigor of Masson pine seeds, seed vigor of Chinese fir might become lower, even lack of vigor. So, DA tested in Chinese fir

seeds with poor vigor might give no expression to the actual vigor levels.

The EC test can reflect seed membrane integrity of different quality seed lots. EC has been well developed for seed vigor assessment of pea as ISTA rule. Besides, it has also been applied to a wide range of crops as well as trees (Artola et al. 2003; Matthews and Powell 2006; Matthews et al. 2009). Our study showed that EC was reliable to evaluate seed vigor of Masson pine whereas it was not suitable for Chinese fir until the samples were enough (n=30). It can be seen from Table 1 that seed vigor of Chinese fir was lower than Masson pine, which was proved by the existence of lots of abortive seeds in Chinese fir. A similar study on *Sebastiania commersoniana* demonstrated that the EC test with 24 h imbibitions was more adequate to differentiate among seed lots, but with little efficiency to discriminate among seed lots with intermediate vigor or with low quality differences (Santos and Paula 2009). Another study showed that EC was lack of accuracy on seed vigor assessment of cucurbits and rice (Pandey et al. 1990; Padma and Reddy 2002). The result of Chinese fir may be interpreted by that of forage species, that is, seeds with poor germination or even dead seed had a similar EC as seeds with high germination (Wang et al. 2004).

The oxygen sensing technology, developed by ASTEC Global, measures the percentage of oxygen in closed microtiter plates in regular time intervals. The purpose of the measurements is to relate the oxygen consumption of seeds over time to seed quality and vigor. It is well known that oxygen consumption is directly and proportionately related to energy use. Thus, a seed’s energetic potential can be determined by measuring its oxygen consumption in a simulated field environment. Because of this proportional relationship between oxygen consumption (respiration) and caloric energy consumption (metabolism), robust inferences for a seed’s performance in the field can be made. To characterize a greater population or seed lot, measuring seed respiration and metabolism is thus very precise and accurate using Q2 instrument. Therefore, oxygen sensing technology by measuring energy use can quickly give insights on seed vigor and provide a great room to seed vigor testing of so many species (Zhao et al. 2009).

In our study, RGT and OMR was the optimal index to evaluate seed vigor of Chinese fir and Masson pine, respectively. RGT provides data that describe the ranking and the homogeneity of germination of a seed lot and gives us the opportunity to differentiate between seed lots for this field emergence speed. OMR is one of the important parameters that can be used to describe the vigor of a seed lot, which was an ideal index for seed vigor assessment of sweet corn under laboratory condition (Zhao et al. 2009). The speed of germination also directly correlates to the field emergence. Because there is a direct relationship between the amount of oxygen consumed and the amount of energy used, this rate value is well related to the speed of germination.

According to ASTEC Global, IMT can be used as the qualifying point for scoring germination of sugar beet seeds. However, IMT was not significantly correlated to field emergence performances of Chinese fir and Masson pine in 2009. The result is likely related to that IMT will be affected not only by the ability of the seed to imbibe the necessary water to increase its metabolism in the germination process but also by environmental factors among different years. According to ASTEC Global, COP is another important parameter that can be used to determine the vigor of a seed lot. This value expressed as a percentage of oxygen reflects how the seeds will perform under oxygen stressed conditions. Such stress may occur in cold and wet soils, or when there is a water film created around the seeds. However, COP was not significantly correlated with field emergence performances except for Chinese fir in 2010. The results indicated that the sensitivity of germination to oxygen partial pressure was likely to depend on the species, temperature, dormancy state and physiological status of the seeds (Bradford et al. 2007).

Oxygen sensing technology was related with the other traditional methods such as laboratory germination. In our study, IMT, COP, RGT were negatively correlated with GP, GI; OMR was positively correlated with their laboratory germination performances. Oxygen sensing test can be used to detect maximum germination under various environmental conditions (Zhao et al. 2009). These results suggest that oxygen sensing data reflect not only the levels of seed vigor but also the performances of seed germination. According to Woodstock and Grabe (1967), more vigorous seed respiration is, higher dehydrogenase activity is. Similarly, DA was significantly negatively correlated with RGT in Chinese fir (r=-0.641, n=30) and Masson pine (r=-0.574, n=30) in our study. However, there were lack of evidences in the relationship between oxygen sensing technology and EC test.

Seed vigor is more difficult to describe than seed viability, but is equally as important for establishing seedlings in the field. Research in this area has established the importance of seed vigor on stand establishment and has begun to elucidate some of the underlying mechanisms for seed vigor. However, it is very difficult to discover a test that will work on all species kinds for all field conditions. Sometimes a combination of tests is used on a seed lot to read its planting potential more accurately. In our study, OMR in combination with GP, GI, EC will create a more reliable assessment for seed vigor of Masson pine. In view of rapidnes, of course, OMR and EC are all good indicators for seed vigor assessment of Masson pine whereas RGT is the only suitable index for that of Chinese fir.

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